GRD RESEARCH NOTES
No. 70

LOCATION OF A LUNAR BASE

John W. Salisbury
Charles F. Campen, Jr.

October 1961

GRD

GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

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Research Instrumentation Laboratory
GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
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Bedford, Massachusetts

Abstract

All pertinent factors governing lunar base location have been discussed and an initial site suggested accordingly. The two major theories of lunar substructure are reviewed as pertinent to the location of a lunar base. The meteoric theory, to which the authors subscribe, favors a moon base located in the highlands where the collapse hazard is at a minimum. Lunar probes for experimental verification of these conclusions are discussed; experimental verification in addition to the Ranger series probes is proposed. Surface characteristics would not particularly limit base location, but natural resources play a most important part. Mineral deposits must be large, centralized, and predictably located. It is suggested that vital water deposits may be found beneath chain craters and rilles, again suggesting a highlands location. The lunar base will have important consequences for astronomical research. Two observatories located 180° apart on the equator can continuously monitor the entire celestial sphere. Aspects of the lunar base as a communications relay also suggest two equatorial sites 180° apart to maintain virtually constant contact. The per capita, per day needs for oxygen, nitrogen, and water of lunar-based personnel are detailed; solar energy as a power source for mineral extraction is proposed. The initial location of a space vehicle terminal is limited by present propulsion systems to the western quadrant of the visible lunar face. Because of tremendous surface variations in temperature, the major lunar base complex would be underground. After detailed consideration of all the foregoing factors, a site south of the Hyginus Rille, near the crater Agrippa, is suggested for an initial lunar base site.

Acknowledgments

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LOCATION OF A LUNAR BASE

Introduction

During the past few years many specific locations have been urged for a lunar base from many points of view. These points of view have, in many cases, been biased toward a particular discipline and have not included adequate consideration of the relation of the geological and environmental factors to the problems of design, supply, function, and operation of a lunar base. Because of the imminent capability for establishment of a lunar base, it is important to outline the pertinent factors and place them in perspective with respect to present and future space exploration capabilities. An analysis of these factors is especially important in order to determine the major areas of uncertainty, so that appropriate research programs may be planned for resolution of these uncertainties prior to actual design and establishment of a lunar base.

An attempt has been made to consider briefly all the pertinent factors and establish their significance and relation to one another. Previous literature on this subject has been critically reviewed and considered. The geology of the moon and its relation to a lunar base location has been discussed. The few known facts are set forth; the opposing theories of lunar formation and the consequences of each in terms of lunar interior and surface structure and natural resources are discussed in detail. The surface environment of the moon is briefly discussed. The various possible uses of a lunar base and the requirements for base location are discussed. Finally, the possible designs of a lunar base, its logistic system, and the operation of these are briefly considered and related to choice of lunar location.

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1. Geology

GENERAL

Complete information is unavailable on the lunar geological problems involved in base location. As a result, it is necessary to extrapolate from theory to provide provisional solutions to these problems as working hypotheses. At the same time, it is important to note any evidence supporting these hypotheses and to point out methods for their future experimental verification.

Geological problems involved in base location are divided into three areas: (1) subsurface structures, (2) surface characteristics, and (3) natural resources.

Subsurface structure, according to the volcanic theory of the origin of lunar features, should favor base location in the maria. However, the subsurface structure to be expected under the meteoritic theory would favor base location in the highlands. The latter theory appears most likely to the writers.

Surface topography and microtogeography should not appreciably affect base location, according to the meteoritic theory of crater origin, but are expected to be more favorable for base location in the highlands. The key factor in surface characteristics is the nature of the lunar dust. Evidence is strongly suggestive of a sintered dust layer.

Natural resources will probably be the most significant factor in base location. It is suggested that large concentrations of mineral deposits, composed largely of H_2O, will be found beneath rilles, chain craters, and domes at maria margins.

SUBSURFACE STRUCTURE

The subsurface structure of the maria and highlands varies, of course, according to one's theory of origin of the major lunar surface features. At this time two main theories of the origin of these features exist, the volcanic theory and the meteoritic theory. The writers do not subscribe to the

volcanic theory and those holding this view are presently in a minority in this country. However, considering certain discrepancies in the meteoritic theory, it would appear the height of folly to totally ignore volcanic concepts in a serious discussion.

With this premise, let us first examine lunar structural characteristics as predicted under the volcanic theory. Modern proponents of this theory[13] generally hold that lunar craters are caldera structures produced when molten material is blown from beneath the surface, emptying a lava reservoir and fracturing the overlying rock. The overlying rock collapses into the empty chamber, producing a depression surrounded by a ring of expelled debris. The common central peaks in the lunar craters are thought to be due to subsequent ordinary volcanism and the maria are considered examples of more widespread internal melting.

Several predictions concerning subsurface structures may be made on the basis of the volcanic theory. It is apparent that the highlands should exhibit a complex of overlapping collapse structures containing layers of pyroclastic debris (largely ash), extrusive vesicular lavas, and intrusive dikes and sills. These are all overlaid, in many cases, by the lava flows and pyroclastics of the volcanic central peaks (Fig. 1). Considering the lower lunar gravity (one-sixth earth normal), very large lava caverns are probable because of the greater possible unsupported roof span. Russell[32] has described lava caverns formed in the Snake River Plains of Idaho when a rigid crust develops over a flowing lava stream and remains as the roof of a cavern when the flow of lava recedes. The Snake River caverns are as large as 70 ft in diameter and 400 ft long, indicating the tremendous possible size of lunar lava caverns. The collapse hazard of both lava caverns and vesicular lavas would make lunar operations in the highlands extremely difficult.

According to the volcanic theory, the maria would exhibit much simpler structure than the highlands. One would expect a highly vesicular surface layer grading downward into solid lava and disturbed only by scattered wrinkle ridges, rilles, domes, and late craters.

The lower lunar gravity would produce a greater thickness of vesicular material on the moon than would occur on the earth and would also result in larger near-surface vesicles. Near zero atmospheric pressure cannot be

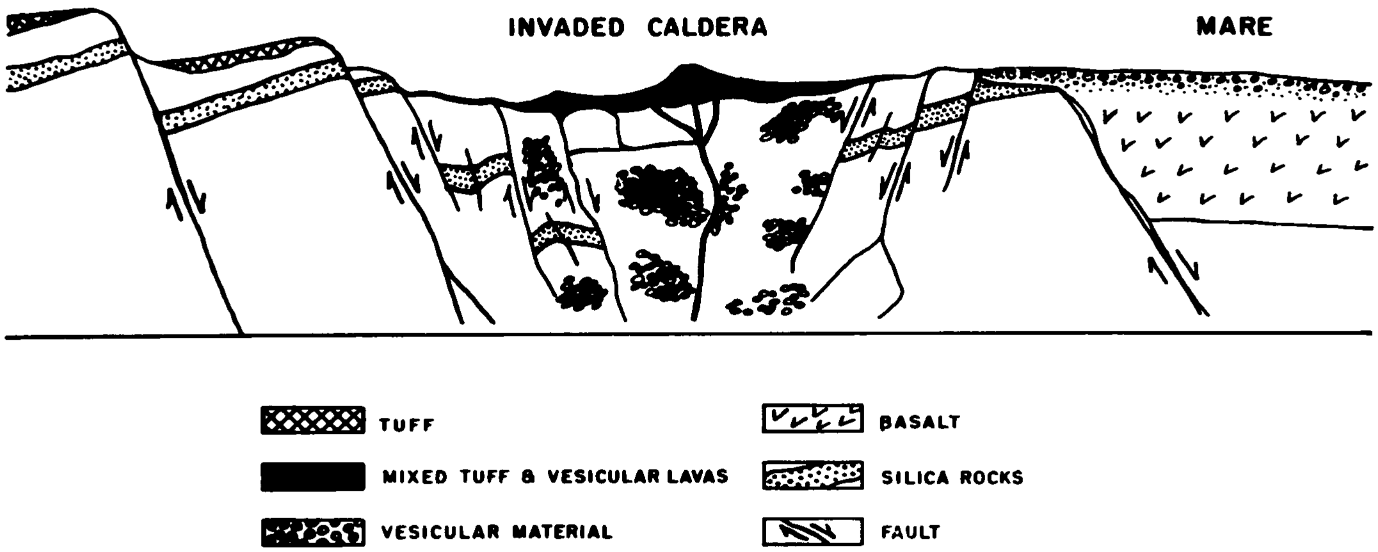

Figure 1. Lunar subsurface structure under the volcanic theory. Large amounts of vesicular material and fault structures present a collapse hazard. (Slightly modified from Green, 1960, page 96)

called on, however, to produce even more extreme vesiculation, because the extensive degassing involved in the formation of craters and maria under the volcanic theory is thought to have produced a temporary, but thick, lunar atmosphere.[11] Even assuming an atmospheric pressure equal to that of earth, however, the lower gravity could produce vesicles of significant size if terrestrial analogies are to be trusted. Such analogies appear to be the only method of obtaining some concept of vesicle size, even though it is a highly speculative concept. Shrock[35] reported that terrestrial vesicle pipes caused by the coalescence and migration of bubbles in lava flows range in diameter from 1/5 in. to 6 in., and may be as much as 6 ft long. It is apparent from field relations that the largest vesicle pipes are produced by steam generated in underlying wet ground or by over-ridden air. These data are useful, however, for a concept of maximum pipe size, which might well be achieved during a lunar degassing. Thus, the maximum expectable size of vesicle pipes under the lower lunar gravity would be 3 ft in diameter and 36 ft deep (six times the size of terrestrial vesicle pipes). The maximum depth of vesicular material would probably be on the order of 36 ft. Assuming a standard (Poisson) statistical distribution of vesicle sizes, the probable, as opposed to maximum, size of vesicles (pipes are generally rare) would be about 1 1/2 ft in diameter. The probable depth of vesicular material would be about 20 ft.

Lava caverns are also a possibility on the maria, although the simple circular maria are usually thought to be great lava pools rather than the product of lava flows. In this light, lava caverns are very unlikely, as the crust on a pool should rise and fall with the level of the lava beneath. Thus, under the volcanic theory, the maria also appear to present a collapse hazard. Due to the greater degree of regularity, the collapse hazard appears less likely to be beyond the bounds of design compensation in lunar operations than that found in the highlands.

The meteoritic theory of origin of the major lunar features holds that they are related directly or indirectly to high-speed impact of meteorities or other external objects. The craters are thought to be the direct result of impact, although later volcanism, perhaps related to the impact, is generally called upon to produce the flat floors of some craters.[1]

Under the meteoritic theory, the highlands subsurface structure should

consist of a highly fractured basement rock overlaid by discontinuous layers of rubble, rock flour, and meteoritic material (Fig. 2). Except in the case of craters which have been subsequently filled with lava, this subsurface structure should exhibit very little collapse hazard and be very favorable for lunar operations.

The subsurface structure of the maria under the meteoritic theory is very similar to that envisioned under the volcanic theory. However, as no general lunar degassing is called for, the lunar atmosphere is considered to be less dense, although some gas would necessarily be evolved from the molten maria. If we assume that melting of lunar material to form the maria produced the degassing of one-half the volume of material degassed under the volcanic theory, then an atmospheric pressure one-half that estimated under the volcanic theory is reasonable. Thus, if no other factors were involved, near surface cavities could double to reach a maximum of 6 ft in diameter. The depth of the vesicular layer would increase by only about 12 percent, due to the continued lithostatic pressure of the overlying material. A maximum depth for the vesicular layer would probably be about 40 ft. Again, the probable dimensions would be about one-half the maximum figures.

Thus, it is apparent that the collapse hazard presented under the meteoritic theory makes the maria less favorable for lunar base location than the more stable highlands. This is, of course, from a subsurface structure point of view.

Having derived some concepts of lunar subsurface structure from theoretical considerations, we must investigate any evidence which might be present on the moon to support these concepts.

Some difference between the structural characteristics of the maria and highlands is indicated by study of the ray craters. Continental ray craters show a strong dependence of the length of their rays on the diameter of the crater, but maria ray craters do not show the same dependence.[23]

Also, more ray craters are found on the maria than on the continents (ratio 3:1); whereas, considering relative areas, the ratio should be 1:3.[15]

The nature of this difference between the maria and continents is revealed in a study made by Gilvarry[11] of the depth-diameter ratios of craters formed on the maria and in the highlands. He found that they fall on two different curves, with the curve for maria craters falling in a region of

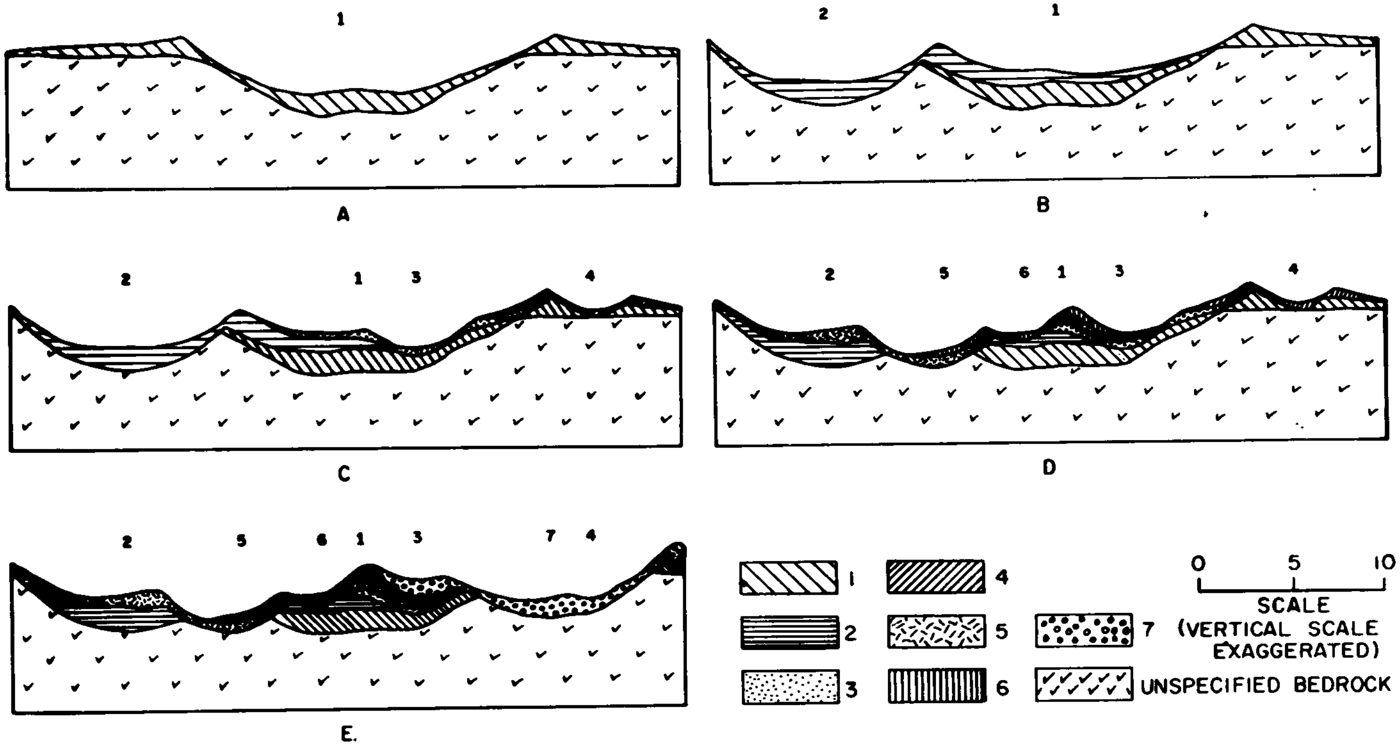

Figure 2. Creation of simplified lunar subsurface structure by meteoritic impact. A single crater with its associated debris is shown in A, and a second crater is created beside it in B. In C, two smaller craters (3 and 4) have penetrated the debris of the older craters, and in D two overlapping craters (5 and 6) have added to the complexity of the structure. A final large crater (7) has destroyed most of crater 4 in E. Actual lunar structure will be even more complex. Negative accretion would change the thicknesses of the layers, but not the essential structure.

less shear strength. The difference indicated to him that the rocks forming the maria are composed of less coherent sediments from ancient seas, while the highlands are composed of more coherent igneous rocks. Another, and perhaps more likely, explanation is that the maria are covered with vesicular lavas, while the highlands are covered with compacted rubble.

The evidence brought forth above is strongly suggestive, but not proof, of the nature of the lunar subsurface structure. Further experiments must be fully planned to clarify this problem. However, it can be tentatively concluded at this time that the subsurface structure of the lunar highlands consists of a highly fractured basement rock overlaid by discontinuous layers of rubble, rock flour, and meteoritic material. The subsurface structure of the maria should consist of a highly vesicular surface layer grading downward into solid lava, and distrubed only by scattered wrinkle ridges, rilles, domes, and late craters. The vesicles should reach a maximum size of 6 ft in diameter, and a maximum depth of 40 ft. Probable dimensions would be about one-half the maximum figures.

Experimental verification of these conclusions will be accomplished by lunar probes. In the immediate future, the Ranger series of lunar probes may offer some degree of verification. Although accelerometers are to be installed on the semi-soft landing packages, they are designed to record the deceleration of the protected instrument package rather than the deceleration of the overall structure. Considering, however, the difference in deceleration of the package for impact on solid rock, or even loose sand, as opposed to impact on 40 ft of vesicular material, the accelerometer may give gross information on the characteristics of the near-surface structure. Further, the hard landing portions of the probes will act as artificial meteorities for which the velocity and mass are known. The brightness of any flash produced upon impact would give semi-quantitative information on penetrability, since the partition of kinetic energy on impact into mechanical energy, heat, and light will depend on this parameter. Finally, and most important, the seismic experiment proposed by Press et al[29] should provide at least a rough indication of the structure in the vicinity of the probe.

However, the measurement that can be made from the Ranger series of lunar probes are point measurements. As these measurements may be misleading, it is necessary to conduct surveys over large areas of the moon. For

survey purposes a lunar satellite appears more practical than a surface vehicle, if proper instrumentation can be designed. In this connection, radio waves show promise of detecting underground structure from altitude. Green[14] and Khmelevskoy and Frolov[18] have reported successful use of the "radio comparative" method in determining the subsurface geology of the north Ural bauxite basin. This method uses low frequency radio waves (about 100 kc/sec) and involves measuring variations in intensity of the electro-magnetic field of long-wave radio broadcasting stations. Further experiments using related techniques referred to as "radar geology" are being conducted by the Waterways Experiment Station of the Army Engineers.

Other, more well-known, geophysical techniques might also be employed in a lunar satellite or hovering vehicles, as detailed by Green[14]. Of these, a gravimeter in a hovering vehicle would probably provide data most easily interpreted in terms of subsurface structure.

Failing all indirect techniques, it may be necessary to gain an idea of subsurface structure by simply increasing the number of point measurements. The number of point measurements may be increased either by means of a rain of sensors from a satellite or by means of tests by automatic roving vehicles.

SURFACE CHARACTERISTICS

According to both main theories of crater origin, and to obvious visible evidence, the highlands are more rugged than the maria in terms of gross topography. Although it is well known that slopes are not as steep as they appear under low illumination with shadow exaggeration, the visual impression of ruggedness is so vivid that it appears wise to illustrate the actual relief (Figs. 3, 4, and 5). It should be emphasized that, although the lunar surface is smoother than it appears, craters with diameters less than 50 km have mean inner slope angles of about 28°. The surface relief is, therefore, by no means negligible, because craters of this size comprise the vast majority.

Both theories of crater origin predict that large amounts of rubble should be present on all of the highland surfaces and on the maria surrounding late craters. Lahee[21] reports that coarse gravels consisting of angular fragments (breccias) have maximum angles of repose of about 35°, and an

angle as high as 42° has been recorded. Should the coarse lunar crater debris assume such slopes, ignoring for the moment possible infilling by finer material, the surface roughness in terms of tens of feet (microtopography) would make lunar operations extremely difficult. However, there are reasons to believe that crater debris will not be a problem. Kopal[20] has suggested that lunar seismic waves caused by the impact of large meteorites or small planetesimals might have strong effects on surface structures. Certainly the debris of early craters would be shaken into low relief and a maximum density packing arrangement by the surface seismic waves of later craters. Only coarse debris surrounding the latest craters should present a surface roughness and landslip hazard. As a corollary to this, it is possible, as suggested by Gilvarry[10], that the apparent erosion of the older lunar craters is a result of their steady destruction by seismic waves. Certainly a large number of severe quakes would tend to reduce the height of the crater walls and produce infilling of crater floors with the wall debris. This might explain the rather severe scatter in plots of crater depth or rim height vs crater diameter.

However, seismic effects on surface characteristics are not confined to the meteoritic theory. The lunar degassing envisioned in caldera formation would also entail strong seismic action from internal structural readjustments. The degassing should also provide for cementation of the debris both by lava flows and by deposition of soluble salts by liquids and gases evolved from the interior, making a favorable adjustment of crater debris in response to seismic waves less complete than under the meteoritic theory.

Therefore, it appears from extrapolation of the meteoritic theory that crater debris in the highlands, far from being a hazard, should present a favorable surface for lunar operations. Under the volcanic theory, the degree of favorable adjustment is doubtful and would probably be less than under the meteoritic theory. In the latter case, the adjustment should be as favorable as fragment size and size range will permit. The debris in particularly favorable areas, not adjacent to any large craters, might even be shaken down into a near equivalent of a compacted road bed.

Both the volcanic and meteoritic theories agree that the maria are lava plains, and predict a similar microtopography for them. This microtopography should consist largely of burst vesicles. The vesicles should reach a maximum of about 3 ft in diameter and 1 or 2 ft in depth under the volcanic

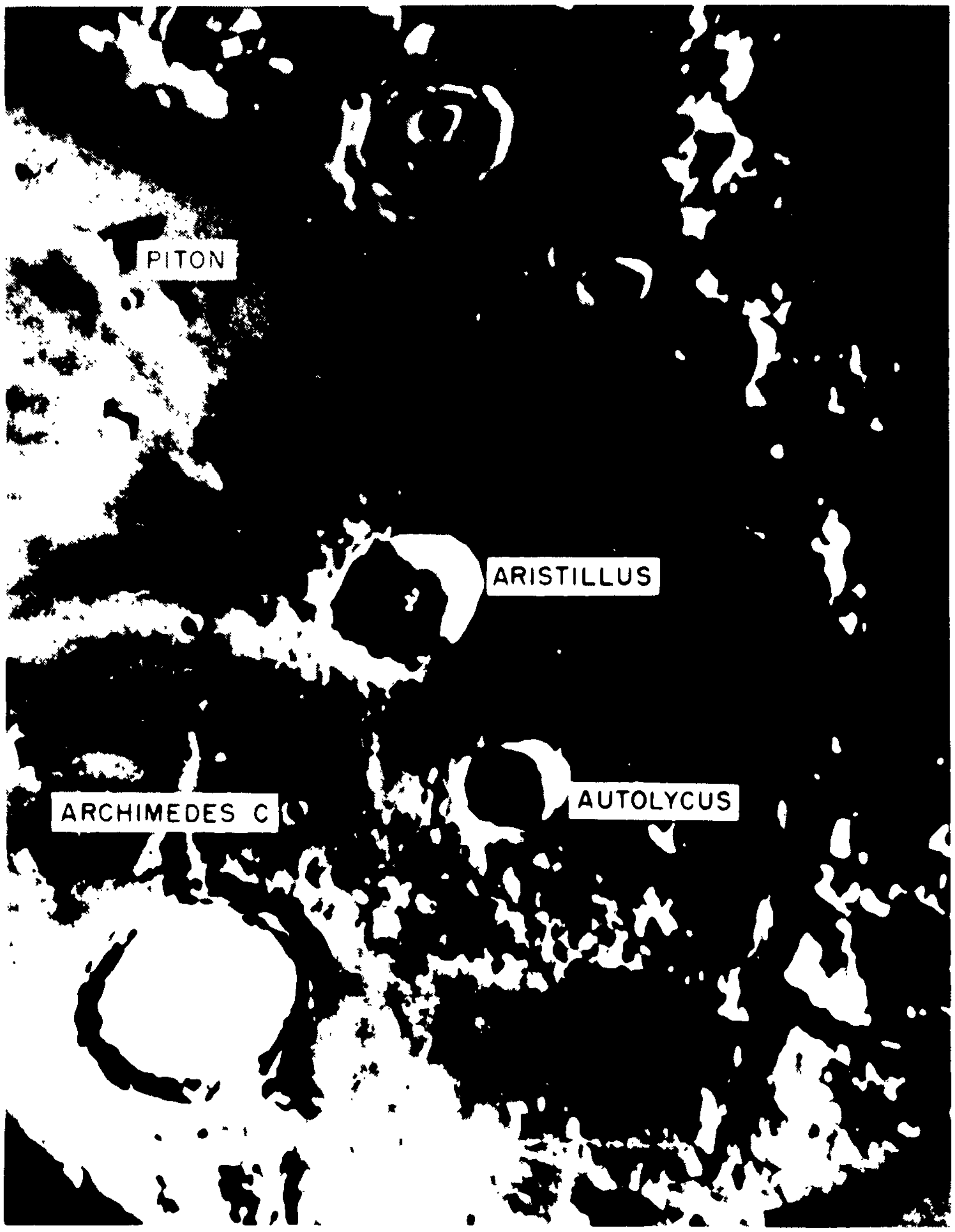

Figure 3. Detail of Mare Imbrium, showing the mountain Piton and the craters Aristillus, Autolycus and Archimedes C. Pic du Midi Observatory photograph.

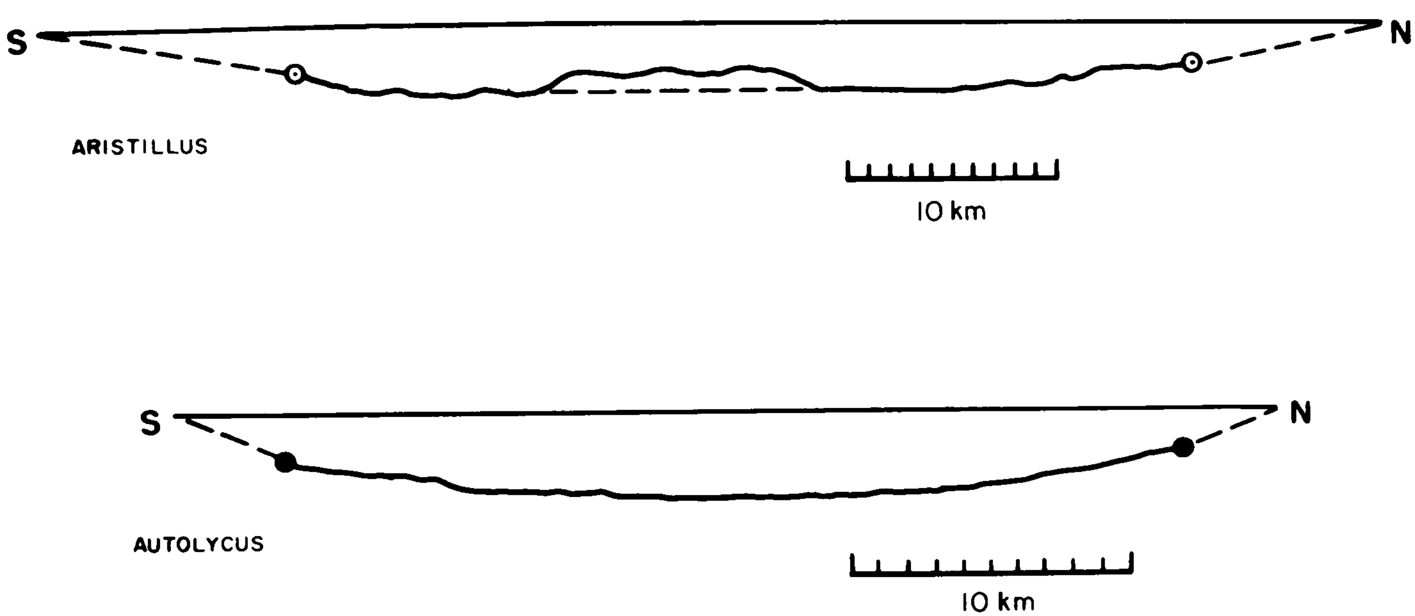

Figure 4. Topographic profiles across the craters Aristillus and Autolycus by Thomas Rackham (1959).

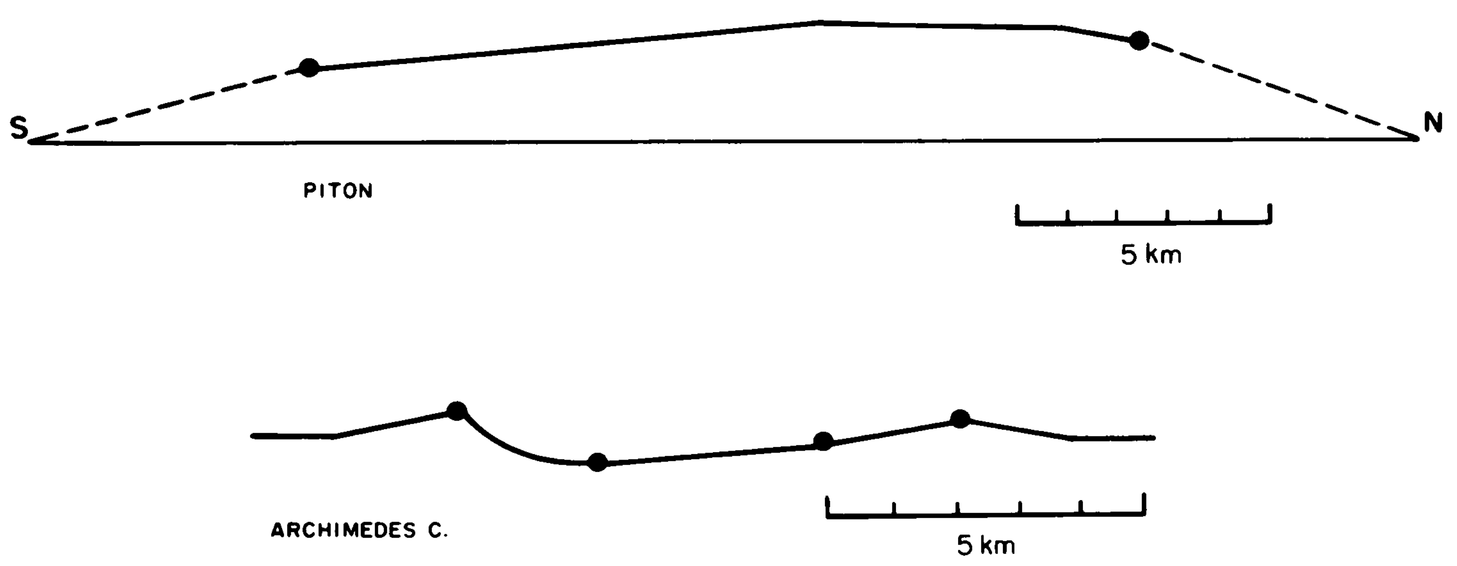

Figure 5. Topographic profiles across the crater Archimedes C and across the mountain Piton by Thomas Rackham (1959).

theory, and 6 ft in diameter and 3 or 4 ft in depth under the meteoritic theory. Probable vesicle size should be about one-half this value.

Both theories also predict dust on the moon. The volcanic theory holds that the dust should consist of volcanic ash as well as meteoritic and fragmented lunar crustal material. No matter how the dust was produced, there are those who feel that it is very deep,[12] and calculate its depth from the amount of material evidently removed from the older "eroded" craters. Gold[12] believes that the average depth of dust on the moon is 1 km and that the maria are, in fact, composed of dust rather than lava. Whipple[43], on the other hand, shows that some of the material involved in high energy explosions will attain velocities greater than the velocity of escape from the moon. Thus, the amount of material so lost may possibly exceed the amount accreted. If the moon does actually "suffer negative accretion", then the depth of the dust layer may remain at a constant (and probably low) level, defined by the masses and velocities of the meteorite flux.

Two extremes are also predicted for the behavior of the dust. Gold[12] holds that electrostatic forces are likely to be significant for small particles, and may arise both from solar radiation and corpuscular streams. Migration of such charged particles could take place from higher ground to large approximately flat regions. The top few feet would be effectively "in suspension" and would be extremely loose, lacking any bearing strength.

Whipple[43], on the other hand, maintains that the influx of solar corpuscular radiation would produce sputtering, which would cement together dust grains on the lunar surface. The sputtering would be assisted by the addition of a certain amount of heavier gases falling onto the lunar surface from the interplanetary medium and by gases vaporized from meteoritic impact (see also Wehner et al[42]). Whipple also maintains that the lunar surface could not carry a strong electric charge because interplanetary space is a relatively good conductor (10^3 electrons/cm^3 near the surface). Further, Roche[30] has found that outgassed surfaces in a vacuum show a strong tendency to adhere structurally to each other when jarred (vacuum welding), probably by virtue of the fact that there is no interstitial air to prevent the full exercise of Vander Waal's forces between surfaces.

Thus, it is expected from these theoretical considerations that the dust will be cemented into a low-density, semiporous matrix. It would be weak

compared with normal sedimentary rocks on earth, but strong compared to a layer of earth dust,and not subject to migration.

Having obtained very different predictions of maria microtopography, depth of dust, and dust behavior from theoretical considerations, it is important to obtain evidence clarifying the role of these three variables. Obviously, the lunar surface characteristics will change drastically with changes in these variables. Should the dust layer be deep, for example, it will submerge the most rugged microtopography. If the dust layer is shallow, it may or may not smooth out the microtopography, depending upon the ruggedness of the topography and the dust's capability for migration. Knowledge of these factors and how they might vary from place to place on the moon is of extreme importance. It appears that a key factor in unravelling these interlocking variables is surface roughness on a scale of tens of feet.

The major line of evidence for surface roughness is provided by radar measurements. Not long ago it was agreed[5, 36, 31, 39] that the lack of limb reflections of radar pulses indicated that the lunar surface was very smooth on a 10 cm scale, most slope angles being less than 12°. More recent measurements[26, 22] have shown that the apparent lack of limb reflections was due to the low sensitivity of previous receivers. Efforts to interpret these new data[4] indicate, more than anything else, how extremely complicated the situation has become. Radar evidence appears promising for the future when it is better understood. However, radar evidence is not reliable enough for present use.

Photometric studies provide a second line of evidence for surface roughness. Struve[37], reporting on the work of Van Dieggelen and others, has shown that the lunar surface is probably heavily pitted. This agrees with the findings of Barabashov[2] and Sytinskaya[38] who maintain that the "microrelief" of the lunar surface is very great.

A line of evidence for the thickness of the surface dust layer is provided by thermal radiation measurements. Pettit[27] concluded that the insulating surface layer, which he believed to be pumice, was 2.6 cm thick. Jaeger and Harper[17] found that their infrared curves fit best for a surface layer 2 mm thick of dust over pumice or gravel. Gibson[9], following the work of Piddington and Minnett[28], found that radiation at 0.86 cm wavelengths indicated an average dust thickness of 2 or 3 cm.

The fact that all of the above measurements agree within an order of magnitude is very encouraging, and appears to support Whipple's[43] hypothesis of negative accretion.

Thermal characteristics are also an indicator of dust behavior. Klein[19] has made some preliminary experiments and calculations which indicate that the dust can not be sintered by sputtering and vacuum welding because thermal conductivity values on the lunar surface are so low. The dust might then exist as a loose powder with minimum point contact of individual particles. If the dust is loose, as Klein[19] maintains, it appears to the writers that this can be only by virtue of the electrostatic charging mechanism advocated by Gold[12]. Other mechanisms have been called upon to put the dust in suspension, such as Gilvarry's suggestion[10] that seismic waves were responsible, but none appear effective on a continuous basis.

It is possible to make deductions concerning the looseness of the lunar dust from observations of the characteristics of lunar features themselves. The lunar rays, for example, have retained their distribution and shapes for at least 300 years. No matter what the rays are composed of, any appreciable rate of dust migration should have long since covered, or at least altered, them. Thus, we can say that the dust probably does not migrate at an appreciable rate, but may nevertheless be charged and loose.

If, as is generally believed, the lunar rays are composed of finely divided material (rock flour), then the variation of ray brightness with phase angle is a second line of evidence indicating that the dust is sintered. Bobrovnikoff[3] reported that the curves of variation of brightness have sharper peaks near the time of full moon for rays than the curves for neighboring regions. If solar radiation does produce an electrostatically charged dust, then the number of dust particles "in suspension" above the lunar surface should reach a maximum at a phase angle of 90°. The scattering and self-shadowing effect of such particles would than act as a brightness inhibitor and tend to produce a smooth curve rather than a sharply peaked one.

Such deductions from the observed characteristics of lunar features are strongly suggestive of a sintered lunar dust layer, but unfortunately are based upon assumptions of the nature of the lunar features observed. The assumptions are that the rays are not self-replenishing and are composed of finely

divided material. Nevertheless, it appears at this time that the microrelief is great, that the dust layer is thin, not loose, and does not migrate.

In order to prove conclusively that the lunar dust is either sintered or loose, a characteristic of the dust itself must be measured that is directly related to the property of "looseness". Thermal conductivity appears to be such a characteristic because it will vary as the number of point contacts between dust particles vary, and the number of point contacts between particles defines the looseness of the dust.

Thus, if the dust bears an electrostatic charge, the strength of this charge will vary with the intensity of solar radiation and corpuscular streams. As the strength of the charge varies, the thermal conductivity of the dust will also vary as the number of point contacts between individual grains increases or diminishes.

Should all efforts to determine lunar surface characteristics from earth fail, then the lunar probe penetrometer and seismic experiments mentioned in the previous section should finally resolve many of these questions. However, it appears that it should be possible to determine many of the lunar surface characteristics without resorting to such expensive methods.

NATURAL RESOURCES

On earth, natural resources often dictate the location of a town or city with no regard to favorable or unfavorable subsurface structure and surface characteristics. It would appear that appropriate natural resources could play an even more important part in the location of a lunar base.

Limited amounts of useful materials may be present on the lunar surface. Vestine[40], Green[14] and Watson et al[41] have calculated that such a useful material as water has a vapor pressure sufficiently low at -150°C to remain for millions of years in the solid phase at zero pressure. Such pressure-temperature conditions may reasonably be assumed at the bottom of such craters as Newton, which are in perpetual shadow, and in shadowed portions of cracks and various other types of surface cavities. These deposits should contain gases leaked from the interior and remnants of the former lunar atmosphere produced during the general lunar degassing and/or maria

formation. However, it is doubtful whether mineral deposits of this sort would be a factor in base location. Though relatively common, they would be small, scattered, and somewhat random in their location. Thus, mining such deposits would not be very economical and they would probably correspond in usefulness to pegmatite deposits on earth.

To be truly useful and effective in controlling base location, mineral deposits must be large, centralized, and predictable in their location. The main purpose of this section is to predict the location of such deposits.

Both main theories of maria origin hold that they are composed of lava. However, some disagreement remains concerning the internal structure of maria in general and of some maria in particular. Even so, a reasonable hypothesis[5] is that the circular maria are not made up of many thin layers or sheets of lava, but originated as giant lava pools. Overflow of these pools produced the irregular maria and, as a result, these maria may be made up of lava sheets.

If an idealized lava pool is followed through its cooling cycle (Fig. 6), the following phases might be expected to occur:

In phase one, the lava pool is created by whatever means and over it forms a highly vesicular crust.

In phase two, the vesicular crust acts as a slowly thickening insulating blanket sealing off the pool from the surface. Thus, the rate of cooling drops sharply and crystallization processes follow those of a buried magma chamber (e.g. Stillwater Complex, Skaergaard Complex). Normally, this appears to involve initial formation of high temperature minerals, their settling through the melt to the bottom of the pool, and slow differentiation of the melt as lower and lower temperature minerals are formed and withdrawn from the remaining liquid as it cools.

In phase three, reduction in volume with crystallization will produce sinking of the central portion of the crust. Thus, volatile constituents of the magma, which are largely excluded from the crystallized minerals, are gradually segregated near pool margins.

Volatiles involved in volcanism on earth are usually: H_2O, CO_2, SO_2, H_2S, HCl, and NH_3. Water is by far the most abundant component, with CO_2 second[24]. Each of these volatiles may act as a carrier of other elements under favorable circumstances. It is generally believed that many terrestrial

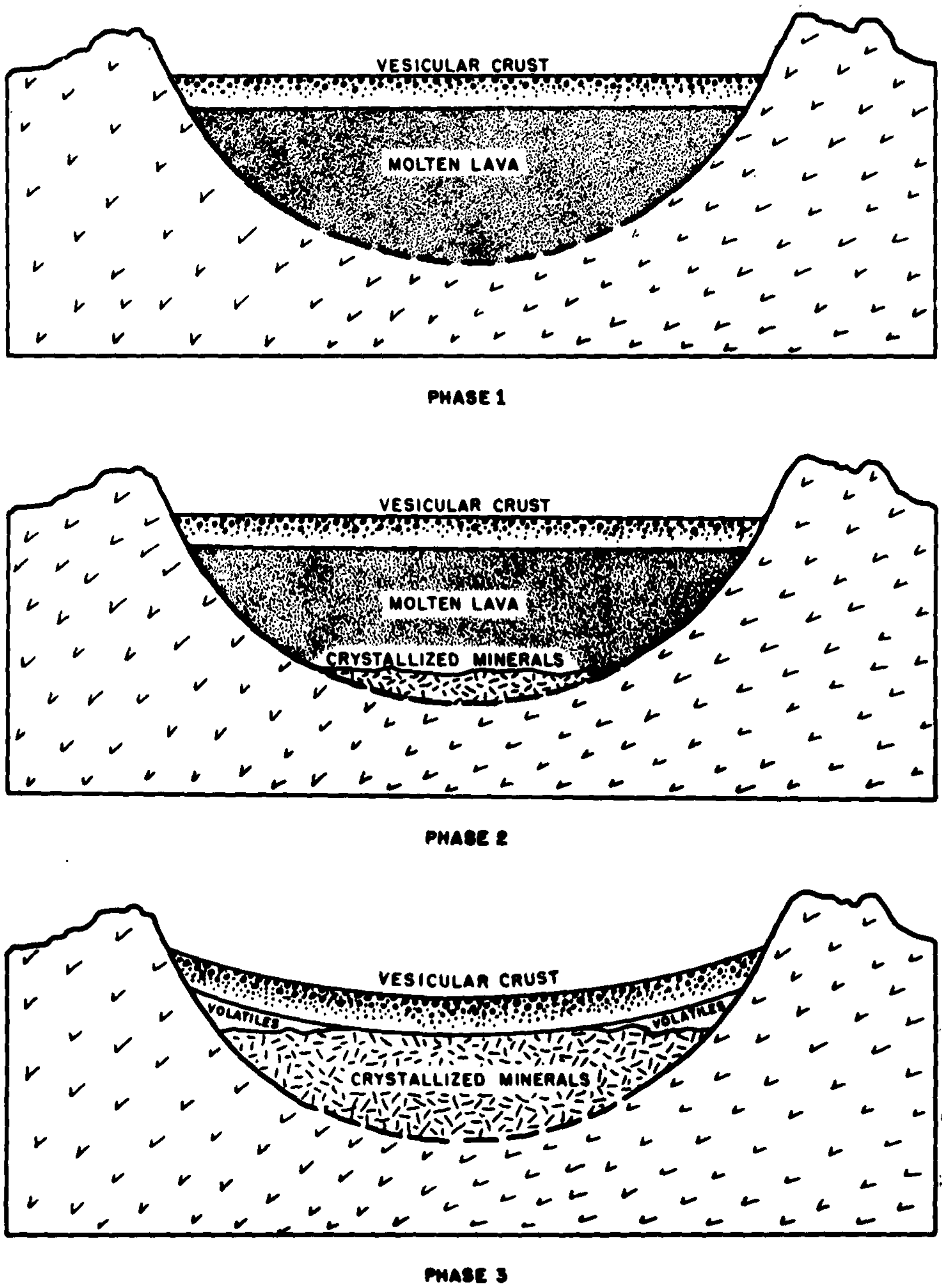

Figure 6. Phases in the creation of volatile concentrations at maria margins. Mare several hundred kilometers in diameter. Vertical scale greatly exaggerated.

mineral deposits are created by precipitation of a valuable element from a solution of volatiles created during magmatic processes. However, creation of most terrestrial mineral deposits requires several cycles of concentration and reconcentration in order to produce large deposits of any but the most common elements. Although an active volcanic past, which might provide such cyclic reconcentration, may be assumed for the moon under the volcanic theory, it is very doubtful under the meteoritic theory. Thus, Green[14] has called for relatively large deposits of various volcanic sublimates to have been formed in the highlands during the lunar degassing, and he would probably call for significant amounts of rarer elements to be dissolved in the hypothesized marginal maria concentrations of volatiles. The writers, as proponents of the meteoritic theory, believe that the volatiles would carry only the more common elements. It seems reasonable to assume that the major volatile carrier would be water, and that the major elements carried would be silicon, oxygen, and iron. Carl Sagan[33] suggests that complex organic matter, derived from the primeval lunar atmosphere and buried on the lunar surface, might survive to the present day. This suggestion should be kept in mind as an interesting, though unlikely, possibility. As water would probably be the most valuable of all minerals on the moon, its hypothetical high content is a desirable factor, and the search for water will be considered as the primary function of lunar resource exploration.

Having predicted from theoretical considerations that volatiles will be concentrated near the margins of the circular maria, it is necessary to look for evidence of this concentration. According to Baldwin[1], an examination of the lunar surface indicates that the lunar rilles, though subsequent to the maria, are so clearly associated with their margins that some characteristic of the lava flows must have been the cause of these features. The location of these rilles is illustrated in Fig. 7. It will be noted that several rilles are associated not with the margins of maria but with lava-filled craters such as Alphonsus, which may be considered as miniature maria. One important feature of rilles is their association with chain craters. Perhaps the best known example is a group of chain craters running N-S between the craters Copernicus and Eratosthenes (Fig. 8). Each chain crater is connected by a rille, and at the northern end of the line the individual craters begin to merge until they almost take on the appearance of a normal rille extending out into

Mare Imbrium. Many other examples can be cited of rilles with similar craters spaced along their length or at their beginning and end. The most prominent such rille is illustrated in Fig. 9.

In discussing the origin of these features, Baldwin[1] stated: "Craters of these types rarely, if ever, show raised rims and are thus set aside as a distinct class from the majority of normal craters. There does not seem to be any question but that they are volcanic blowholes of some kind and are directly the products of gases contained in the moon's crust." It will also be noted (Fig. 7) that rilles commonly parallel the overall conjugate fracture pattern of the lunar crust which has been mapped by Bulow[6], Fielder[8], Hackman[16] and others.

It would seem from the characteristics of rilles and chain craters discussed above that they are probably related to each other and to gas deposits associated with the maria. The writers believe that, subsequent to maria formation and concentration of volatiles near maria margins, lunar quakes produced by meteorite impacts or internal disturbances revitalized preexisting fractures in the lunar crust. The fractures were able to tap many of these gas concentrations. Escape of this gas produced circular blowouts along each fracture which commonly were so closely spaced as to produce a general widening of the fracture to form a rille, aided by graben-like collapse with the release of pressure.

If, then, volatiles were concentrated near maria margins, and if rilles and chain craters were formed by the release of such volatiles, what conclusions may be drawn as to the location of lunar mineral deposits? First, it appears reasonable to suppose that the initial fumarolic phase of hot gas release in rille formation would slowly degenerate into a hot spring phase of liquid flow, followed by a cold spring phase, and then quiescence as the mare cooled and the volatiles were exhausted. This last phase would probably entail gradual sealing of the liquid flow channels with deposits of dissolved minerals, most likely quartz. Considering that the present temperature of the lunar subsurface is approximately -23°C, according to Mezger and Strassl[25], there might also be large deposits of ice sealed off beneath the surface, depending upon past and present lunar thermal gradients. Certainly considerable amounts of hydrated minerals suitable for simple water extraction would be expected. Thus, large deposits of water in some form are probably to be

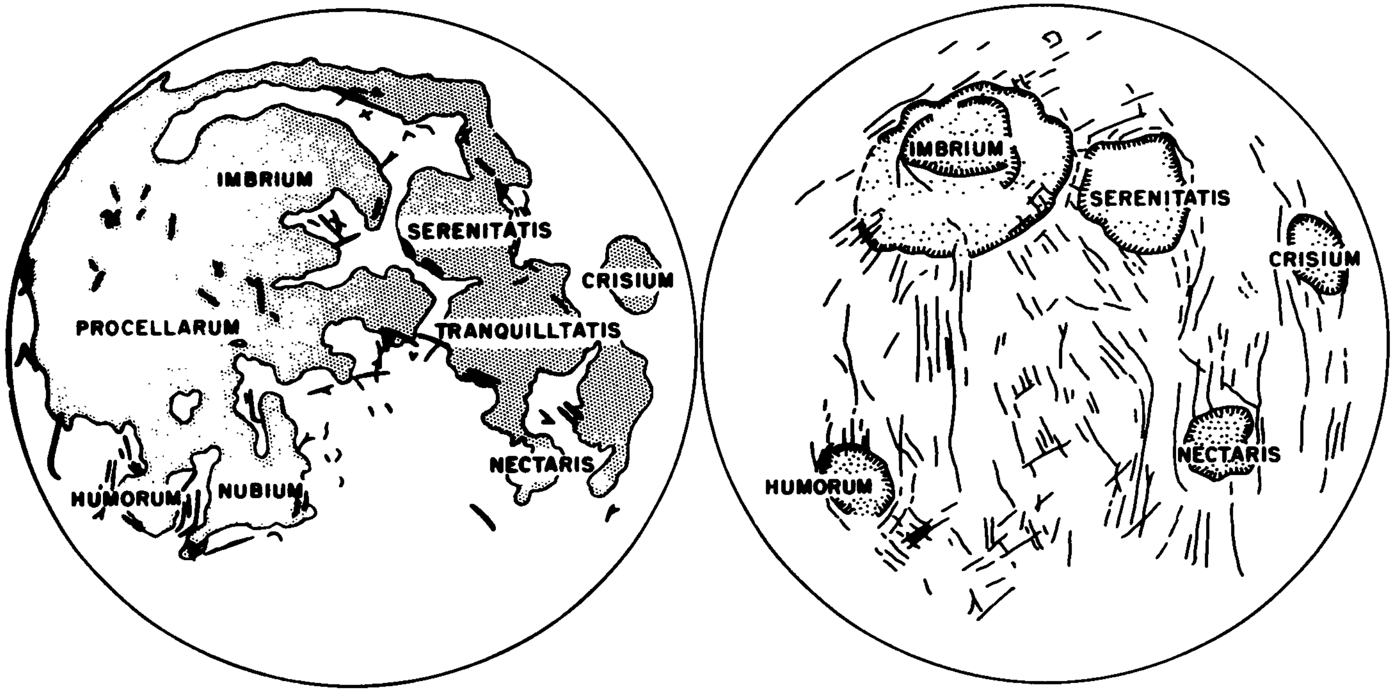

Figure 7. Distribution of major lunar rilles (left), modified from Baldwin; 1949, p. 198. Simplified lunar tectonic patterns (right), modified from Bulow; 1958, p. 595.

Figure 8. Chain craters (upper left) between Copernicus and Erathosthenes. Mt. Wilson Observatory photograph.

Figure 9. The Hyginus Rille (left) and Ariadaeus Rille (right), with Mare Tranquillitatis at far right and Mare Vaporum at top left. Mt. Wilson Observatory photograph.

found beneath the chain craters and rilles, along with deposits of the other volatiles and any elements they may have carried.

It should also be noted that other features of the maria, especially the domes, may have been formed by some process related to the release of trapped volatiles. One of the writers has suggested, in a previous paper,[34] serpentinization (hydration) of olivine by slow water leakage from the interior as the cause of lunar domes. Urey (personal communication) has extended this concept to also apply to wrinkle ridges. These features may, therefore, also be sites of large-scale water deposition.

Continuing experimentation is, of course, required to verify the conclusions reached above. The seismic experiment proposed by Press et al[29] may accomplish this or at least give rough indications of structure. It is especially important that more advanced lunar probes (Surveyor, Prospector) do some of their proposed core drilling in the vicinity of rilles, for more definite information. Other techniques sensitive to water or hydrogen, such as neutron albedo measurements, would most appropriately be used over or near rilles or edges of mare.

GEOLOGICAL SUMMARY

An effort has been made to define the geological problems involved in the establishment of a lunar base, to deduce provisional solutions to these problems from the two main theories of the origin of lunar features, to point out any evidence in favor of these solutions, and to propose experiments for their final verification.

Geological problems involved in base location may be divided into three groups: (1) those concerned with subsurface structure, (2) those concerned with surface characteristics, (3) those concerned with natural resources.

Subsurface Structure

According to the volcanic theory, location of the lunar base in the highlands would be difficult due to the collapse hazard presented by lava caverns and caldera structures. The maria would present more favorable sites for

base location because the collapse hazard represented by the vesicular surface should not be beyond the bounds of design compensation.

According to the meteoritic theory, location of the lunar base in the highlands would be permissible because the discontinuous layers of rubble, rock flour, and meteoritic material overlying the highly fractured basement rock would not present a collapse hazard. The maria, on the other hand, are considered to bear near-surface cavities probably twice the size of those predicted under the volcanic theory. This added collapse hazard, when compared to the negligible collapse hazard of the highlands, makes the highlands a more favorable site for base location, and such a site is advocated in this report.

Surface Characteristics

The gross topography in the highlands, though quite rugged in appearance, is actually not rugged enough to hinder base location. The microtopography (on a scale of tens of feet) produced by rubble ejected from the craters also should not hinder base location, at least in the case of the meteoritic theory. Under this theory, which is considered here to be the most likely, lunar seismic waves caused by large meteorite impacts should have shaken the rubble into a maximum density packing arrangement with low relief. Under the volcanic theory, despite internal seismic disturbances, adjustment should be less complete due to the cementing action of lava flows and atmospheric processes. Both theories predict that the microtopography of the maria should have a relief not exceeding three or four feet, and probably less.

Very different predictions have been made for the depth of the lunar dust and its behavior. It may be deep or shallow, sintered or loose, and capable or incapable of migration. Evidence points to a shallow, sintered dust, but further experiments are necessary for confirmation.

Natural Resources

It appears that appropriate natural resources could play an even more important part in base location than structure or surface characteristics. Remnants of the lunar atmosphere and gases leaked from the interior are

probably present in the shadowed zones of deep polar craters and surface fractures. Such deposits, though common, would probably be small, scattered, and somewhat random in location. It appears, on the other hand, that large concentrations of volatiles should occur near maria margins during solidification of the lava, and that these concentrations may have been tapped by revitalized fractures to form rilles, chain craters, domes and wrinkle ridges. Therefore, it is probable that large centralized mineral deposits, composed largely of H_2O, will be found in association with these features.

Considering the probable lunar structure, surface characteristics and natural resources, it appears that the lunar base should be located in the highlands near a rille, but not near a recent large crater such as Copernicus or Kepler. Also bearing in mind astronomical, guidance, and propulsion requirements for a base near the equator and in the center of the lunar face, a location in the highlands just south of the Hyginus Rille, near the crater Agrippa (8°E long., 5°N lat., on Fig. 10, Lunar Map), is provisionally proposed for the lunar base.

2. Base Function

GENERAL

A lunar base could be utilized for unique physiological, astronomical, and high vacuum plasma and solid-state physics studies; as a communications relay station; for mining and refining lunar minerals; for fabrication of other bases and interplanetary vehicles; as a launch site for interplanetary operations; and, of course, as a site for earth-moon flight operations. This latter function is discussed briefly in the section of this report on Base Design and Operations. For physiological, high vacuum plasma and solid-state physics studies, the low gravity, lack of a significant magnetic field, and very low atmospheric pressure are of principal importance. Because this environment is essentially constant over the lunar surface, these studies may be conducted without regard to a particular site location. The remainder of the suggested base functions are discussed in the following sections.

ASTRONOMY

A tremendous potential exists for an astronomical observatory based on the moon because of the absence of a substantial atmosphere. Observations of the sun, earth, other planets, and stars may be conducted in extensive regions of the electromagnetic spectrum not accessible to an observer on the surface of the earth. The regions of the spectrum accessible to an observer on the moon will span the X-ray, ultraviolet, visible, infrared, microwave, and long radio-wave domains, and will be limited only by the response of detectors available. Further, because of the lack of image distortion due to a turbulent atmosphere, image fidelity will be limited only by instrument quality. Thus, a completely new vista which promises startling revelations about the nature of our universe is opened to the astronomer on the moon. Therefore, it is anticipated that establishment of an astronomical observatory on the moon will be one of the primary purposes for which a lunar base will be created.

Observation of celestial objects from an observatory located on high ground on the lunar surface will be conducted with equal facility for objects near the horizon as well as for objects near the zenith, because of the lack of an absorbing, scattering, turbulent atmosphere. The complete hemisphere will be useful at a lunar observatory, in contrast to the two thirds to one half of a hemisphere useful at an earth-based observatory. During the lunar day, sunlight scattered by the lunar surface will be a minor problem but amenable to solution. An observer on high ground on the lunar surface will be able to see a complete hemisphere; therefore, two observatories located diametrically opposite one another would be able together to continuously monitor the whole celestial sphere.

If the observatories were located at the lunar poles, the portion of the celestial sphere visible at either one of the observatories would remain essentially constant. The apparent motion of the stars during each lunar day would be circles having a common center at the zenith. Because of the inclination of the lunar equator to the ecliptic, the apparent motion of the sun during a lunar day would be approximately circular, but with its elevation angle varying during the course of a year from 1 1/2° above the horizon to 1 1/2° below the horizon. The earth, on the other hand, would appear relatively

stationary, moving in a small ellipse centered over zero degrees selenocentric latitude and longitude. This motion would extend from about 8° east to about 8° west longitude, and from about 6° elevation above the horizon to about 6° depression below the horizon. The earth would show to observers on the moon, phases similar to those the moon shows observers on earth. The relation of these phases to the apparent position of earth will vary yearly, with the full earth visible at its maximum elevation above the horizon of an observer at the lunar pole only once each year. The planets, with the exception of Pluto, will appear to an observer on the moon to move in a zone of the sky approximately 8° on either side of the eliptic. The inclination of the orbit of Pluto is about 17°. Thus, to an observer at a lunar polar observatory the planets would always be near the horizon and, depending on orbit phase and inclination, be above or below the horizon. Mercury will appear to move in a spiral which will carry it from a maximum elevation angle of about 3° to below the horizon in times ranging from half a lunar day to about two lunar days, because of its relatively short period of revolution. Pluto would be visible above a lunar polar horizon for more than 100 years.

Eclipses of the sun by the earth would correspond to lunar eclipses as seen from the earth, and would be observable from a point near a lunar pole only during the six terrestrial months that the "new" earth is above the horizon. Because of the large size of the earth, solar eclipses seen from the moon would often involve obscuration of much of the solar corona as well as the photosphere. This obscuration may permit measurement of light, scattered by the very tenuous solar gases at many solar radii from the sun, which is too faint to be seen from earth. Refraction and scattering of sunlight by the terrestrial atmosphere during such an eclipse will produce a small illumination of the moon which will hinder observations of the very faint light from coronal streamers. The duration of totality for solar eclipses as seen from any specific point on the lunar surface will be about two hours at a maximum. When an observer on earth can see a solar eclipse (i.e., an occultation of the sun by the moon), an observer on the moon will be able to see the shadow of the moon moving across the surface of the earth, taking a maximum of about four hours to cross from one side to another. The maximum cross section of the umbra will be approximately 170 miles. The boundary between the umbra and penumbra will be relatively sharp in comparison with that seen

from earth during lunar eclipses, because of the lack of a lunar atmosphere. An observer at a lunar pole observatory would be able to see this phenomenon only if it occurred during the six terrestrial-month period when the full earth is above the horizon.

If the two lunar observatories were located 180° apart around the lunar equator, each would see at any instant half the celestial sphere, the portion visible at either one of the observatories constantly changing with a periodicity approximately equal to the lunar day. Superimposed on this would be a cyclic annual variation. The apparent lunar daily paths of the stars would be 180° arcs of circles, in planes parallel to the plane of the lunar equator. The sun would rise over the eastern horizon, pass within 1 1/2° of the zenith, and set beyond the western horizon (see Fig. 10). The earth will, when seen by an observer at the lunar equator, appear relatively stationary, moving in a small ellipse centered over the point on the lunar surface at zero degrees selenocentric latitude and longitude. An observer at Sinus Medii, near the crater Agrippa (8°E longitude, 5°N latitude), would see the earth always within 8° of the zenith, and for him the middle of the lunar night would be brightly illuminated by earthshine from the full earth. As the lunar night wore on, he would see the full earth wane until at sunrise the last crescent of the old earth would fade. The planets would, when visible, always appear in a sector of the sky within 8° on either side of the path of the sun. All planets would be observable for two weeks (or half a lunar day) of every month (lunar day). Eclipses of the sun by the earth, and earth by the moon, could be seen only by a lunar equatorial observatory located on the face of the moon visible from earth. All such eclipses, except some partial eclipses of the sun, could be seen by a lunar equatorial observatory located between 82°E and 82°W lunar longitude.

If the lunar observatories were located at points other than at the poles or along the equator, the apparent motions of the celestial objects would fall between the two extremes just discussed.

It is apparent from the preceding discussion that location of a lunar observatory at the poles would permit observation at each observatory of half the stars all of the time; whereas, for equatorial locations, all of the stars could be observed half of the time at each observatory. Observation of the earth, planets, and sun from polar locations would be subject to some

difficulty because of their erratic motions with respect to the horizon, whereas at an equatorial location, all these objects would be observable at regular intervals.

During times of full earth, illumination at the surface of the moon near Sinus Medii is a hundred times greater than the illumination produced on earth by the full moon. This will be about 1 1/2 foot candles during full earth and diminish to about 1/10 foot candle at quarter earth. The Van Allen zones around the earth will be a source of electromagnetic and corpuscular radiation, and the many radio stations on earth will constitute a relatively strong radio-noise source. Thus for sensitive photometric, spectrometric, or radiometric observations of faint celestial or cosmic sources, the earth will provide an unceasing, perturbing background at an observatory located on the face of the moon visible from earth.

It is clear then, that for general astronomical purposes two lunar bases located 180° apart on the lunar equator, with one located between 82° W longitude and 82°E longitude, would provide maximum utility.

COMMUNICATIONS RELAY

The moon offers a potential site for the relaying of intelligence between points on earth, between the earth and the planets, between the earth and space vehicles, and between space vehicles. The advantage a lunar communications base would have over a similar facility on earth would be related principally to its lack of a substantial atmosphere, except for earth-to-earth relays where its utility is principally due to its high vantage point. This lack of an atmosphere on the moon would permit the use, for communications with space vehicles, of portions of the spectrum which cannot penetrate the earth's atmosphere, and would also permit the use of higher power levels at radar antenna feeds beyond those which cause ionization of the air and subsequent arcing at the earth. Communications between the moon and the planets would be limited to those portions of the spectrum which penetrate the specific planetary atmospheres concerned.

The relaying of information between points on earth via the moon is potentially of limited value because of the intermittent nature of the moon's visibility from two widely separated points on earth. For this reason, and

because of the large power or antennae required, relays via the moon would be less desirable than relays via a net of close terrestrial satellites. However, a potential requirement exists for direct communications between the earth and moon base in the event that the base is established before a net of communications satellites is established around the earth. A location on the face of the moon between 82°E and 82°W selenocentric longitude and between 84°N and 84°S selenocentric latitude would be mandatory for such communications. Beyond these limits a relay station would at times be obscured by the limb of the moon. If the relay station were located at zero degrees selenocentric latitude and longitude, in Sinus Medii, antennae would be required to scan over angles about the zenith not greater than 8° in order to point at the earth. Such small angular scans could be readily achieved either mechanically or electrically. Because the antennae will point nearly vertically all the time, mechanical construction will be simplified.

For communications between the earth and planets, between the earth and space vehicles, and between space vehicles, the moon offers a potentially valuable relay site upon which the necessary large high-gain antennae and associated equipment could be established. A moon site offers an advantage over an artificial terrestrial satellite because of the existence of a gravitational field, of a large growth potential, and of possible proximity to a general-purpose moon base. A location in equatorial zones of the moon would be desirable, as in the case for general astronomy. Regular contact with vehicles near the planets could be achieved for two continuous terrestrial weeks each lunar day. Two sites placed 180° apart would be able to maintain continuous contact with the vehicles, except for short periods of time when they were hidden by the earth, sun, and the planet, and except for those times when the vehicle passed near the moon and through the 2000-mile wide blind zone perpendicular to the line joining the two sites. If each of the sites were located on high ground, so that they could see below the horizontal, the blind zone would be contained in the common volume of two right circular cones. The cones would have their apexes at the site and their axes of revolution coincident with the line joining the sites. For an elevation of 600 ft above the mean lunar surface level in the vicinity of the site, the bases of these cones would have radii of about 60,000 miles. If the antennae were located on a

prominence such as the rim of the crater Agrippa, which is about 3000 ft above its surroundings, this radius would diminish to about 30,000 miles; and if located on the peak of Mount Piton at about a 6000-ft elevation, this would further diminish to about 20,000 miles. Substantial reduction of this blind zone below these limits will require additional sites, or use of supplementary equipment aboard lunar satellites.

Communications between bases on the moon by conventional means, as by transmission of electromagnetic radiation through space, will be difficult because of the lack of an atmosphere and ionosphere sufficient to refract, scatter, or reflect the electromagnetic radiation around the moon. If surface-based relay links were to be used, a very large number would be required because of the great curvature of the moon. Lunar satellite relay stations are potentially capable of solving this problem; but, because of the influence of earth on their orbits, these stations may require rocket power for maintenance of the desired orbits. If both sites suggested above were located on the face of the moon visible from earth — that is, with a separation of at most 168° in order that they both be visible from earth and able to communicate via earth relay — there would exist a wedge-shaped blind zone of at least 12° centered about the plane perpendicular to the line joining the two sites and passing through its mid-point. The vertex of this wedge would extend at least 9000 miles toward earth. If these sites were located at essentially the same selenocentric longitude, the blind zone toward the back of the moon would encompass the whole of the zone in which the solar system would appear. Thus, the continued observation capability of the two sites with respect to the solar system would not be significantly greater than one site alone. However, if the sites were located along the lunar equator, this wedge-shaped blind zone would encompass only about one twentieth the zone in which the solar system would be seen, hence the combined observation capability of the sites relative to the solar system is 95 percent. The blind zone could be reduced as much as 6° by locating the sites at elevated points on the lunar surface.

MINING AND CONSTRUCTION

Establishment of a manned lunar base will be facilitated if raw materials can be obtained and processed on the moon. The availability of such raw

materials and their probable locations were discussed in the previous section on natural resources. Utilization of these natural resources will require relatively large amounts of energy.

The most urgent need would be for oxygen, nitrogen, and water. The basic requirements of personnel for oxygen will be between 20 and 80 grams per hour, depending on activity and normal metabolic rates of personnel. An average consumption of 40 grams per hour may reasonably be assumed. Nitrogen will be required by personnel as a diluent for the oxygen in amounts initially determined by the volume of structures inhabited, and subsequently at a rate determined by losses due to leakage. An initial structural volume of 6000 liter per person is considered to be a reasonable minimum. Leakage of 10 percent per hour STP would require that about 800 grams per hour of nitrogen and about 160 grams per hour of oxygen be produced per person. Helium has been used as a substitute for nitrogen; and, where a possibility of rapid decompression exists (as would be the case on the moon), it has more desirable properties. However, the probability of finding helium is even more remote than that of finding nitrogen. Water for direct consumption will be required in amounts of about 2 liters per earth day for each person. Closed ecological systems can reduce the requirements for acquisition of fresh oxygen and water, but the energy required for regeneration of these by simple chemical or mechanical means will be similar to that required for their initial separation. At the aforementioned rates, the power required for separation of oxygen, nitrogen, and water from their naturally occurring state will range from 1 to 10 kilowatts per person depending on the particular reaction utilized, neglecting the power required to remove material from its emplacement and prepare it for processing.

Excluding the energy required for physical removal from site to processing area, extraction of elements such as iron, silicon, aluminum, chromium, and copper from their ores will require amounts of energy ranging from 1 to 50 kilowatt hours per pound of refined material, depending on the particular ore and process utilized. In the absence of a specific base plan it is, of course, not possible to determine the anticipated rate of production of minerals such as these. We may, however, make some general estimates. For example, in the United States during 1960 there were approximately 2000 pounds of iron and ferrous alloys produced per each employed adult. If the

base were large and completely self-sustaining, this figure might be a good approximation. On the other hand, if the base were small and intended to supply materials for expansion of the base and for construction of vehicles and materials for other bases, this figure would be low. For example, in the primary metal industries in the United States, each worker produced an average of 80,000 pounds of fabricated metal products in 1960. Thus, the average production rate during working hours could range from 1 to 40 pounds per hour. If the normal 23 percent duty cycle prevalent on earth were applied to personnel of the lunar base, the average production rate would range from 1/4 to 10 pounds per hour. It is more likely that a duty cycle of 30 to 50 percent would be applicable. In this case, the average production rate could range from 1/2 to 20 pounds per hour per person. Using this latter figure with the figure for energy requirements for extraction of minerals, we find that the range of power potentially required is from 1/2 to 1000 kilowatts per person.

Zwicky[44] has suggested that solar energy might serve initially as a source of power. The flux of solar energy on a surface normal to the sun's rays at the lunar surface will be approximately 130 watts per square foot. For direct thermo-chemical conversion, as by heating compounds to cause phase change or disassociation, the net conversion efficiencies, considering absorptivities of the materials, emission of thermal radiation, and optical inefficiencies, might be as high as 30 percent. For photoelectric-electrochemical conversions, the efficiencies might reach 5 percent. Thus from 5 percent to 30 percent of the solar energy could be utilized. To achieve the power requirements stated above, a collector of from 30 to 150,000 square feet per person would be required. Because the sun is in general visible for only half the time, it is necessary to double the required energy collection capacity to supply energy for those processes which must be carried on continuously. These processes are at a minimum — the processing of oxygen, nitrogen, and water. Thus, the collector area required ranges from 60 square feet per person to as high as 300,000 square feet per person, depending on specific functional requirements, the processing techniques available, and ore composition and state.

For the minimal requirements stated above, collectors could be placed on equatorial mounts so that they continuously faced the sun. These small

collectors would function equally well at any point on the lunar surface. Considering the size of solar furnaces having already been constructed on earth, it is reasonable to expect that individual collectors of areas as large as 10,000 square feet could eventually be constructed on the moon. However, the difficulties of fabrication of a moving structure of that size are such that for all power requirements exceeding about 1 kilowatt per person, a more feasible solution might be the use of photoelectric converters placed on the lunar surface facing the zenith. In this case, the energy flux incident on the converters varies with the sine of the angle of incidence, and the energy absorbed may also vary with angle of incidence. Optimistically assuming a receiver surface which absorbs equally well for low and high angles of incidence, the collector area will, for a collector at the lunar equator, have to be increased by approximately 50 percent to compensate for the lesser energy flux at low angles of incidence during lunar morning and afternoon. For collectors at other lunar latitudes, the collector area will have to be increased additionally by a factor equal to the secant of the latitude. Thus, at 45° latitude, the area required would be 1.4 times that required at the equator; and at 60° latitude, the area required would be two times that required at the equator.

The maximum power requirement estimated above is rather large but not unreasonable for a combination smelter, refinery, and foundry, and would require about 7 acres (about 3 city blocks square) of solar energy converters for each person. It seems apparent that such large area solar energy collectors would not be used. At power levels of about 1 kilowatt, the weight of silicon solar energy converters approximately equals that of an unshielded closed cycle nuclear energy converter; and at power levels of about 30 kilowatts, the weight of a turbo-electric solar energy converter approximately equals that of the unshielded closed cycle nuclear energy converter. For larger power levels, the nuclear device weighs less. Since the materials for these components must be transported from earth, it is apparent that for power levels less than 1 kilowatt, silicon solar cells would be utilized; for power levels between 1 and 30 kilowatts, a solar heat engine would be utilized; and for power levels greater than 30 kilowatts, nuclear power supplies would be utilized. A base intended for mining and construction purposes would, on the basis of the estimated above, require power levels in excess of 30

kilowatts, and would therefore utilize nuclear power sources. Therefore, location on the surface of the moon would be principally determined by location of suitable mineral deposits, as described in the section on natural resources, and not by power requirements.

SPACE VEHICLE TERMINAL

The location of a space vehicle terminal will initially be determined by the marginal capabilities of our present and near future propulsion systems. Minimum energy ballistic trajectories to the moon from earth, which terminate in a vertical descent to the moon's surface, will have their termination point on the western quadrant of the moon (see Fig. 10) and in a narrow band on either side of the lunar equator. Because of the lower gravity, launch from the moon is less difficult than from earth, hence the location of a base from which vehicles may be launched towards the earth or other planets will not be initially determined by propulsion requirements primarily. In the absence of other considerations, the optimum site for launching interplanetary or cislunar vehicles is the site which the earth-to-moon shuttle can reach.

As the lunar base complex grows and as transport of materials from one site to another on the moon becomes common, the launch site for interplanetary vehicles may be chosen in accordance with propulsion and communication or other needs. Until that time, location near the site at which earth-moon shuttles land will be necessary. In either event, space terminals are more suitably located near the lunar equator in order to minimize energy required for travel to the earth and other planets.

Extensive exploration of the solar system will require tremendous amounts of fuel. Utilization of fuels mined on the moon will permit a substantial reduction in the size of vehicles used for this purpose and in the amounts of fuel required. In fact, as Clarke[7] points out, such utilization of lunar resources appears absolutely necessary for true exploration of the solar system. With fuel available from lunar resources and with advanced propulsion systems, the fuel penalty involved in location of a lunar base at other than equatorial zones will become a minor consideration.

3. Base Design and Operation

GENERAL

Base design and operations will vary with the specific functions assigned. Regardless of the functions, all will have in common a difficult environment against which men and machines must be sheltered. Base design will be important in base location when designs are chosen which have limited tolerance for lunar environmental factors which vary with location. Thus, if a surface location were chosen and the base design was limited in its tolerance to high temperature, it would become necessary to locate the base away from the lunar equator. Regardless of the specific function, the possible designs of base components may be generally categorized as either surface or subsurface installations.

SURFACE INSTALLATIONS

Surface installations will be principally subject to electromagnetic and corpuscular radiations from the sun and to meteor infall, in addition to the low gas pressure. Other important factors will be the variable temperature of adjacent lunar materials and the presence of ionized gases of low density. For most structures, vertical cross-sectional area will be less than horizontal. For such structures, the total energy input from the sun can be minimized by locations distant from the equator. This would, in general, conflict with overriding requirements set by base function. Shielding could be provided to minimize the impact of solar and meteoritic radiation on the structure. With such shielding, location of the base could be determined by the requirements of the proposed structures for a solid footing. The optimum locations regarding surface bearing strength are discussed in the section on lunar geology.

SUBSURFACE INSTALLATIONS

Although surface installations could be protected against direct solar and meteoritic radiation by shielding, their immediate surroundings will exhibit a 250°C variation in temperature during the course of a lunar day. The large temperature variation imposes large cooling requirements during day and large heating requirements during night. At a small depth below the lunar surface, probably no more than a few feet, the temperature will remain at a constant value near -20° C. A facility located below the surface would be shielded from solar and meteoritic radiation and would experience a constant environmental temperature. For this reason, it has been suggested that the major portion of a lunar base complex be located underground, leaving only those components on the surface which are required by their nature and function. Lunar subsurface structure then becomes the determining factor in base location. This factor has been discussed in the section on lunar geology.

4. Conclusions

The factors considered in the location of a lunar base have been geology, base function, and base design.

Geological considerations suggests that a base should be located near a rille in the lunar highlands. Astronomical considerations suggest that two lunar bases be established 180° apart on the lunar equator, preferably on high ground. Present marginal propulsion capabilities suggest that a base be located on the western quadrant of the visible face, but the possible discovery of a lunar source of rocket fuel and/or future technical advances should make this a minor consideration. A guidance penalty is involved in any base location requiring a departure from a ballistic trajectory, but this is also a minor consideration. Direct communication with the earth without benefit of a relay station requires a base on the visible face of the moon. For continuous communications within the solar system, bases on both sides of the moon are required. A base should be located on or near a high elevation, to provide for maximum range of transmission for surface communications. Base power supplies will probably be nuclear in nature and will have no effect on

base location. Base design will have no affect on base location if the base is built underground.

From the above discussion it appears that the initial lunar base should be located in the highlands near the center of the visible face, as this will best satisfy the majority of the requirements. A site south of the Hyginus Rille, near the crater Agrippa, has been suggested.

As the lunar environment i_ conquered, subsequent bases can be established to satisfy the additional astronomical and communications requirements.

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